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Connected Corridors

Summary of Research

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Partners for Advanced Transportation Technology works with researchers, practitioners, and industry to implement transportation research and innovation, including products and services that improve the efficiency, safety, and security of the transportation system.

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Summary of ICM Research Achievements

Modeling, Simulation, Analysis, and Control of Traffic Corridors

The ultimate and overriding goal of our research in this field is to develop means to intelligently manage and coordinate mobility in a large urban corridor, in order to maximize environmental sustainability, productivity, convenience, and livability. To this end, the Connected Corridors research program was initiated in July 2011 at UC Berkeley's Partners for Advanced Transportation Technology (PATH) to research, develop, and test a framework for future corridor traffic management in California. Connected Corridors was established by unifying the research and development efforts of two major PATH projects: Tools for Operational Planning (TOPL) and Mobile Millennium. The TOPL project, which Professors Horowitz and Varaiya established and direct, focused on the development of traffic analysis, modeling, prediction, and decision support tools for freeway traffic corridors. Mobile Millennium, which Professor Alex Bayen established and directed, focused on the use of mobile and hybrid data for traffic estimation and travel time prediction. A key aspect of Connected Corridors, which sets it apart from previous PATH efforts in this field, is the inclusion of a large-scale pilot deployment that is planned to take place during the next four years in the I-210 freeway corridor in Los Angeles. If this pilot deployment proves successful, it will set a framework and initial blueprint for further Caltrans-led corridor management deployments in other sites throughout California.

A key component of the Connected Corridors program is the development of a macroscopic/mesoscopic simulation prediction-based Decision Support System (DSS) for active traffic management of the I-210 corridor. The envisioned Decision Support System utilizes self-calibration, traffic estimation, demand prediction, and model-based traffic management tools to run a series of short-term (e.g., one-hour) rolling horizon simulations, in order to (a) forecast future traffic conditions under different expected likely scenarios and different traffic management strategies and (b) determine the strategy that will most likely meet traffic management performance objectives if deployed.

To achieve this goal, we have been developing traffic flow simulation models that not only run very quickly, but are also able to adapt quickly and frequently to changing traffic supply and demand conditions, based on current and historical heterogeneous traffic data, and produce traffic forecasts whose reliability can be verified. We have also been synthesizing traffic management strategies that optimize corridor performance, under a set of predicted model parameters and traffic demands and scenarios forecasts, in order to quickly and reliably estimate the best possible performance gain of a management strategy under consideration. Finally, we are working to ensure that a selected traffic management strategy is deployable in a robust manner, subject to frequent traffic sensor and communication faults.

Freeway Modeling, Simulation, Analysis, and Control

Research during this period has addressed several critical elements of freeway corridor traffic forecasting decision support systems:

1) The development of automated statistical-learning techniques for calibrating the capacity and supply characteristics of the roadway segments, based on heterogeneous historical traffic data [1, 2].

2) The development of model-based learning algorithms for accurately imputing (i.e., reconstructing) unavailable on-ramp input flow demands and off-ramp flow turning proportions at ramps that lack detection, using mainline traffic flow data [3].

3) The development of model-based sensor fault detection, exclusion, and model reconfiguration techniques to achieve robust model calibration in the presence of frequent mainline traffic sensor and communication faults, even when unavailable on-ramp demand flows and off-ramp turning ratios must be imputed using sporadically faulty mainline traffic flow detection [4, 5].

4) The development of boundary demand prediction algorithms that are able to forecast the boundary mainline or on-ramp traffic flows that are expected to enter the network and the turning ratios of the off-ramp flows that will exit the network during the forecasting period, based on historical and currently available traffic data [6, 5].

5) The development of model-predictive coordinated on-ramp metering and variable speed limit control algorithms that can determine, in a computationally efficient manner, the traffic management strategy that globally minimizes the total vehicular travel time spent on the roadways [7, 8] or locally decreases mainline traffic flow immediately upstream of a bottleneck section that experiences significant capacity drop [9], for a given set of calibrated supply characteristics and boundary demand predictions.

   Other traffic management strategies, model-based freeway-to-arterial traffic detouring, freeway-arterial coordination, and arterial signal control traffic management strategies are currently under development.

6) The formulation and experimental verification of new queue estimation techniques, based on vehicle re-identification using wireless magnetometer sensor arrays, in order to reliably estimate vehicle queues at the freeway on-ramps and signalized arterial intersections [10, 11, 12]. Monitoring queues at freeway on-ramps and signalized arterial intersections is necessary to effectively manage freeway corridors.

Results in [5, 3] show that the developed calibration, sensor fault detection and handling, and ramp flow imputation techniques can produce traffic flow models that accurately reproduce observed traffic behavior in large freeway network segments for an entire 24-hour simulation period, utilizing only the measured or imputed on-ramp flows and off-ramp turning ratios as inputs to the model. For example, it was shown in [3] that a calibrated macroscopic cell transmission model of a 26-mile long section of I-

210E is able to accurately reproduce observed traffic congestion behavior, while producing relatively small overall density and flow errors (2.63% and 3.58%, respectively) and satisfying most of the fidelity performance benchmarks that are used to evaluate microscopic models by the Federal Highway Administration and many state DOTs. Results in [6, 5] show that the developed boundary demand prediction algorithms can effectively and in a computationally efficient manner forecast mainline and on-ramp traffic flow demands one hour ahead of time, even during days with unusual traffic flow demands, such as a Super Bowl Sunday. Results in [7] show that the developed model-predictive freeway coordinated ramp metering and variable speed limit freeway traffic management schemes can be implemented in a computationally efficient manner, on a large-scale freeway corridor (e.g., a 23-mile segment of the I-80 freeway in the Bay Area) over a ½-1–hour rolling time horizon, in order to determine the traffic management strategy that will minimize total travel delay, including time spent on the on-ramp queues, for a given set of freeway calibration parameters and boundary demand predictions.

Further details are included in the subsections below.

Freeway Modeling, Analysis, and Calibration

A key feature in TOPL and Connected Corridors is the automated, empirical calibration of corridor traffic flow models from traffic data, as originally introduced in [13]. Five-minute traffic flow and density data, obtained at each section of the freeway via the PeMS database system, is used to estimate the key parameters of the Cell Transmission Model (CTM), including free-flow speed, maximum flow capacity, critical density, congestion-wave speed, and jam density. [1] and [2] each present a statistical learning methodology for improving the characterization and identification of these parameters. [1] explores the use of probabilistic graphical models to represent the joint probability distribution of section capacities located along a freeway. [2] explores the statistical learning estimation of the flow-versus-density fundamental diagram as a probability density distribution in both the free-flow and congested traffic regimes. Such distributions can be used either to estimate the expected values of the parameters, in order to conduct deterministic traffic flow simulations, or to conduct statistical simulation studies in decision support systems.

Ramp Flow Imputation

Accurate access to on-ramp flow demands and off-ramp flow data is essential for a traffic flow model to reproduce actual traffic behavior and perform accurate traffic forecasting. In particular, during peak periods when freeway mainline flows are near capacity, small increases in on-ramp demands or small decreases in off-ramp split ratios can trigger congestion, resulting in large increases in travel time and producing large deviations in the resulting density and speed. Unfortunately, data from freeway ramps, particularly off-ramps and freeway-to-freeway interconnection ramps, are often missing or incorrect. A key innovation introduced in TOPL is the model-based imputation (e.g., generation) of missing on-ramp flows and off-ramp flow split ratios using neighboring mainline traffic flow data.

[3] analyzes the convergence properties and presents experimental results of an iterative learning algorithm introduced in [14] for imputing on-ramp flows and off-ramp turning ratios, based on the Link Node Cell Transmission Model (LN-CTM) [15]. This imputation algorithm no longer requires the 24-hour periodicity assumption that was required in our previous algorithm ([14]); hence, it can be used to

impute on-ramp flows and turning ratios during any segment of time. Moreover, it can be used in a decision support system to perform imputation of missing ramp flow data in “real time.” In the first step of the imputation procedure presented in [14, 3], a discrete-time adaptive iterative learning algorithm is used to estimate the effective input flow demand to each cell of the model. In the second step of the imputation procedure, on-ramp flows and off-ramp split ratios are uniquely determined through the solution of a linear program that minimizes the error between modeled and observed mainline flows. The papers illustrate the application of the imputation algorithm to determine missing on-ramp and off-ramp flow measurements in a 26-mile long section of the I-210 freeway in Pasadena. It is shown that the calibrated LN-CTM with imputed missing on-ramp and off-ramp data is able to accurately reproduce observed traffic congestion behavior, while producing relatively small overall density and flow errors (2.63% and 3.58%, respectively) and satisfying most of the fidelity performance benchmarks that are used to evaluate microscopic models by the Federal Highway Administration and many state DOTs.

Sensor Fault Detection and Handling

A frequently encountered problem with freeway traffic data is that it is often faulty, due to sensor damage, transmission errors, vandalism, etc. This problem is aggravated when unknown on-ramp demands and split ratios must be imputed in order to perform traffic forecasts, since the ramp imputation algorithms heavily rely on mainline traffic data.

[4] presents an innovative model-based fault detection and exclusion scheme that implements a decision logic to automatically identify faulty or misallocated freeway traffic sensors in the presence of unknown on-ramp and off-ramp flows. This algorithm is currently being implemented within the TOPL and Connected Corridors frameworks in the form of a fault detection and handling tool that automatically excludes faulty detection stations and reconfigures the calibration, imputation, estimation, and prediction systems accordingly.

[5] presents a case study of the use of the TOPL and Connected Corridors calibration, ramp imputation, and fault detection and handling tools in the calibration of a link-node cell transmission model for the I-680 freeway in Northern California, under severe mainline sensor faults (60% of the mainline vehicle detection stations (VDS) were faulty).

Coordinated Ramp Metering and Variable Speed Limits

On-ramp flow metering is one of the most effective means of decreasing congestion and travel-time delays on a freeway. In ramp metering, traffic entering the freeway through the on-ramp is regulated, while often preventing the resulting on-ramp queue from significantly overflowing onto the neighboring arterials, with the objective of allowing the freeway to operate at maximum efficiency. Speed control (variable speed limits) is primarily used for improving safety, but it has also has been found to be useful for congestion alleviation when ramp metering is insufficient, particularly when it is deployed in a freeway segment immediately upstream of a bottleneck section that experiences a heavy flow capacity drop during the onset of congestion. These traffic control schemes are part of the suite of traffic management options that are being incorporated into the TOPL/Connected Corridors traffic management decision support system under development. [9, 16, 17] describe two novel approaches for implementing Variable Speed Limits (VSL) and Coordinated Ramp Metering (CRM) on freeways.

[9] presents a heuristic but effective VSL/CRM control scheme, specifically designed to decrease mainline traffic flow immediately upstream of a bottleneck section that experiences significant capacity drop, such as the infamous Powell St. bottleneck on the I-80 freeway in Emeryville. [16, 17] present a new class of computationally efficient model-predictive CRM/VSL congestion controllers for freeways that are based on the Link-Node Cell Transmission Model (LN-CTM) used in the TOPL/Connected Corridors framework. In [16] the standard LN-CTM model without capacity drop is considered, while in [17] a modified LN-CTM with congestion-induced capacity drop is considered. It is shown in [16] that the minimization of the total travel time (or total travel delay) in a freeway segment (including time spent at the on-ramp queues) under combined CRM and VSL control can be cast, under a relaxation process, as a solution to a linear program (LP). An approach is proposed to map the LP solution back to the solution of the original optimal control problem, and it is proven that the solution derived from this approach is optimal. A model-predictive framework is used to demonstrate the feasibility of the proposed methodology, even when VSL is disabled, via a realistic freeway-modeling exercise. In [17] the model-predictive methodology presented in [16] is extended for the case when congestion-induced capacity drop and ramp weaving effects are included in the LN-CTM model. Since the resulting optimal control formulation is non-convex, a heuristic solution approach is proposed by partitioning the freeway into segments and placing realistic restrictions on solution trajectories, based on the results of [44]. This allows the computation of the control strategy to be performed as a small sequence of linear programs.

[18] summarize a newly developed model capable of handling the coupled effects of on-ramp queue dynamics and freeway dynamics. These have subsequently been used to derive a set of ramp control algorithms capable of regulating traffic, based on efficient uses of the so-called adjoint-based method [8]. In this article the algorithm is implemented on a model of I-15, based on an original Aimsun simulation.

Freeway-Arterial Coordination and Rerouting

The adjoint-based method was also used in [19] to formulate controllers capable of rerouting flows based on the congestion level on the freeway. The corresponding algorithms figure out the proper split ratios to apply at selected off-ramps to optimize overall throughput when part of the flow is fed to the arterial network and the other part stays on the freeway. To complement this approach, a few other modeling directions have been investigated, in particular the modeling of creeping flow (i.e., smaller vehicles using the space between larger vehicles to overtake them in traffic jams) [20], or the use of a "viscosity term" in the conservation of vehicles to understand how to smooth shocks in traffic and control the corresponding flows (through the Hamilton-Jacobi equations) [21].

In parallel, the problem of routing in traffic networks has been investigated quite thoroughly, in the context of stochastic routing (and the problem of stochastic on-time arrival). The problem there is to understand how one can maximize the chance of arriving on time given a deadline, which is different from minimizing the expected travel time. Several acceleration mechanisms for these algorithms have been developed. [22] It is expected that this line of research will ultimately feed the travel information part of the DSS.

[23] examines the issue of cybersecurity: What would happen if an intruder took over the control infrastructure of the freeway (i.e., metering), as recently demonstrated through the attack on the Sensys network. The corresponding papers show the ability to create “congestion on demand,” i.e., the ability to selectively create traffic jams at a user-specified location and time frame.

Queue Estimation Using Vehicle Re-Identification

As discussed in a previous section, ramp metering is an effective traffic control strategy for managing freeway congestion. However, in most instances it is critical to maintain the on-ramp queues to within the lengths of the on-ramps, in order to prevent their spillback onto neighboring arterial traffic. Frequent on-ramp queue spillback onto neighboring arterials is one of the major sources of conflict between freeway and city traffic managers. Unfortunately, it is extremely difficult to obtain reliable queue length estimates based on existing on-ramp and arterial traffic flow detectors, particularly when the traffic on top of the detection station is congested.

[10] reports on a field test that was conducted on the Hegenberger Road loop on-ramp to I-880 southbound to evaluate traditional and novel on-ramp queue length estimation methods. It was found that a novel queue length estimation method, which relies on counting vehicles entering and leaving the on-ramp but corrects for offset errors using vehicle re-identification algorithms based on wireless Sensys detector arrays, offered the best estimation performance. However, it was also found that the existing vehicle re-identification algorithms underperformed during congested traffic conditions, when vehicles stop and move slowly over the detectors, at the on-ramp entrance.

[11] describes how vehicle re-identification algorithms that are based on magnetometer arrays need to be modified in order to improve their performance under congested traffic conditions. The modified algorithm was tested on the Hegenberger Road loop on-ramp to I-880 southbound and compared to the existing algorithm. It was found that the proposed algorithm modifications not only significantly improve the vehicle re-identification rate but also significantly decreased the vehicle mismatch rate, particularly during congested traffic conditions. The modifications also resulted in accurate on-ramp queue estimations, even under congested traffic conditions, when vehicles stop and move slowly over the detectors, at the on-ramp entrance. [12] presents an arterial traffic travel time estimation field test using vehicle re-identification techniques. It is shown in this study that the modified vehicle re-identification algorithm introduced [11] also outperforms the original algorithm in arterial travel time estimation applications.

Demand Estimation, Prediction, and Management

The traffic corridor decision support system that is being developed in the Connected Corridors program requires demand-prediction tools that are able to forecast the amount of traffic that is expected to enter the network during the prediction horizon, to run a series of short-term rolling horizon traffic flow simulations, in order to forecast future traffic conditions under different expected likely scenarios and different traffic management strategies.

[24] presents a boundary flow prediction method that combines the most recent traffic data with historical traffic data. For each ramp flow in the network, historical data are aggregated to flow profiles

that represent a typical day, one for each day of the week. Using the nominal historical profile as a deterministic input and the actual traffic flow as the noise-contaminated measured output, the parameters of an autoregressive moving average with exogenous input (ARMAX) model that best describes this input/output relation are identified in a real-time recursive fashion. Based on the results of the ARMAX identification process, the optimal multi-step ahead predictor model of the traffic flow, which utilizes the flow measurements up to the current time, is determined. [5] provides a more sophisticated and adaptable demand-prediction scheme by first clustering the historical sensor data using the K-means method to obtain the representative data pattern of the sensor. In this case, instead of using only a single flow profile to represent a typical day, multiple flow profiles are considered, each being the centroid of a K-means cluster. Based on the identified ARMAX model, a D-step ahead optimal predictor is generated for each cluster and its associated estimated error prediction variance calculated. The cluster and its associated ARMAX estimate that produces the smallest estimated D-step ahead error prediction variance is selected at each sampling time instant to generate the optimal D-step ahead predictor of the sensor output. Due to their simplicity and robustness, these methods are useful in practical applications. Results obtained using empirical freeway mainline and on-ramp data show that these methods outperform methods that rely only on the historical average of the data to perform a prediction, especially during days with unusual traffic flow demands, such as a Super Bowl Sunday.

A part of the work has focused on understanding the value of time and the proper pricing structure to incentivize commuters to change their patterns. For example, how much should one person receive in order to accept a change to their routes and take a longer path? Preliminary findings are available in the article [25]. More work is needed on pricing.

Based on this initial work, routing games have been studied, i.e., a setting in which a portion of users are indeed changing their routes for the common good (against some rewards) to decrease congestion. The first problem studied is the Nash Stackelberg problem, in which a set of commuters change their pattern and the rest of the commuters readjust themselves selfishly. This was published in [26]. Then the problem of learning these equilibria was studied, i.e., to understand how, day after day, a population making choices learns from their choices based on the outcome of the previous day. This phenomenon is important and enables us to understand how the population will react to incentivization, should it be given the opportunity to gain some reward for good behavior. [27]

More recent work has focused on the problem of understanding mobility patterns (in particular, OD estimation and the route assignment and route flow inference problems) based on cell tower records. This work is still in its infancy, and partnerships with AT&T and Verizon are just starting. However, the preliminary results are promising and show that we will be able to estimate OD, link density, and volumes, as well as estimate typical routes and flows along them from cellular data [28]. The methods account for demographic and coverage biases, and solve flow inference problems via convex optimization from data without involving traditional modeling assumptions (such as user equilibrium). Under the present-day cellular coverage density in the I-210 region, the methods provide 90% accuracy in route flow estimation. These findings give promise for the use of cellular data sources in operational coordinated re-routing at the corridor scale.

Freeway Model Modifications

After the completion of the I-680 CSMP Project [56], recommendations were made as to how the freeway traffic model could be improved. Two major requirements were:

1. Modify the junction model to better handle multiple incoming flows when output links are congested.
2. Extend the existing HOV model to the separated HOV lane configuration with gated access.

We have introduced a new node model [57], which (1) incorporates user-adjustable input link priorities and (2) relaxes the First-In-First-Out (FIFO) condition for diverging flows. The FIFO condition means that at junctions with multiple output links a jam in one of the output links blocks the whole flow through the junction. The consequence of that is a completely blocked freeway mainline flow in case of an off-ramp spillback. Relaxing the FIFO condition results in partial (not complete) blocking of flows that are directed to free output links, a behavior that is more realistic. Monotonicity and mixed monotonicity properties of a system with relaxed FIFO at junctions are analyzed in [58].

In [57] we introduced the macroscopic model components needed to adequately represent a traffic network with managed lanes: multi-commodity traffic flow, policy for junctions with multiple input and multiple output links, and local traffic assignment, where vehicles of certain types may choose between multiple downstream links. Then, we applied this theory to modeling of freeways with HOV and HOT lanes, and introduced techniques that reproduce phenomena inherent to HOV/T traffic [59]: the inertia effect and the friction effect. The inertia effect reflects drivers' inclination to stay in their lane as long as possible and switch only if this would obviously improve their travel condition. The friction effect reflects the empirically observed drivers' fear of moving fast in the HOV lane while traffic in the adjacent GP links moves slowly due to congestion.

The upgraded traffic model is being implemented in the Berkeley Advanced Traffic Simulator (BeATS) [60] and tested with freeway configurations I-680N (full access HOV lane) and I-210E (separated HOV lane with gated access) in [61].

Freeway Density Estimation Using Probe Data

In an age of ever-increasing penetration of GPS-enabled mobile devices, the potential of real-time "probe" location information for estimating the state of transportation networks is receiving growing attention. Much work has been done on using probe data to estimate the current speed of vehicle traffic (or equivalently, trip travel time). While travel times are useful to individual drivers, the state variable for a large class of traffic models and control algorithms is vehicle density. In this research we derived a method for using probe data to enhance density estimates that had been obtained using roadside sensors, based on Rao-Blackwellized particle filters, a sequential Monte Carlo scheme. Subsequently, we present numerical results showing the utility of our scheme in using probe data to improve vehicle density estimation, with high performance in simulation and good performance with real data collected from a freeway in Los Angeles, California [62].

Loop Detector Fault and/or Bias Identification

Loop detection data that is received through the Caltrans Performance Measurement Systems (PeMS) in the form of flow, density, and speed information is critical for calibrating models, predicting inflow demands, and running model-based decision support systems. Unfortunately, loop detector data often contains biases, and the detectors are subject to frequent faults, which may lead to inaccurate calibrations and predictions if not properly handled.

We have developed a new model-based and multi-step procedure for analyzing loop detector data, in order to identify faulty and/or biased detectors:

1. Perform flow balance tests across freeway links, to pinpoint groups of detectors that include one or more biased or faulty detectors. Although this first test cannot pinpoint the actual biased or faulty detectors, it pinpoints the group of detectors that require further fault identification analysis.
2. Run a model-based fault detection algorithm that imputes ramp flows, in order to match mainline data density measurements, and subsequently identifies faulty or biased mainline freeway loop detectors utilizing an error signature parity match. This step successfully identifies the mainline detectors that are faulty or biased among the group of detectors flagged by the first step of the procedure.
3. Run the same ramp imputation and error signature parity match algorithm as in the second step, but use measured on-ramp and off-ramp flows, in order to respectively flag biased or faulty off-ramp or on-ramp loop detectors.

This fault identification procedure was tested using loop detector data from Interstate 210-W in Los Angeles, California, obtained from PeMS. Results obtained from a particular day's analysis indicate that the developed loop detector fault and/or bias identification procedure is working reliably. To test the algorithms, the fault identification algorithms in the second and third steps of the procedure were run independently from the first step. Most of the mainline and ramp loop detectors that were identified as faulty or biased by the second and third steps were also flagged as being part of a group of faulty detectors by the first (flow balance) step of the procedure, and were correctly diagnosed as being faulty by further human analysis. Additional loop detectors were identified as being faulty and/or biased by the second and third steps of the fault detection algorithm, which were not flagged by the first (flow balance) step. However, a subsequent human analysis involving the local flow values of the regions surrounding each of these detectors show that the flagged detectors were indeed faulty and/or biased. These flow imbalances, however, were of low enough values to not be registered by the first (flow balance) step of the identification procedure. Additional numerical analysis is in progress, and a complete progress report is in preparation.

Arterial Modeling, Simulation, Analysis, and Control

Research during this period has addressed the following critical elements of arterial traffic modeling, calibration estimation, and forecasting in decision support systems.

Arterial CTM Model Calibration and Testing

The Cell Transmission Model (CTM) and its extended models have been applied in both traffic simulation and control design, for both freeway traffic and urban street traffic. However, to date there have been very few studies that analyze the accuracy of Cell Transmission Models when they simulate urban street traffic. [29, 30] discuss the calibration and evaluation of an arterial Link-Node Cell Transmission Model (LN-CTM) developed under TOPL using the Lankershim data set generated by the Next Generation Simulation (NGSIM) project of the Federal Highway Administration (FHWA). The Lankershim NGSIM data contains detailed vehicle data on a segment of Lankershim Boulevard that is close to Universal Studios in Los Angeles. The segment has four signalized intersections and intersects, from north to south, with one off-ramp from US-101, Universal Hollywood Dr., and James Stewart Ave/Valleyheart Dr. In total, there are 11 entering roads and 10 exiting roads in this network. The NGSIM vehicle trajectory data was generated by video from five cameras and real-time signal timing data. The vehicle trajectory data was processed to obtain the model parameters, demands, and exit flow split ratios, as well as link vehicle densities and vehicle queues and flows at the intersections.

Simulation results showed that the link-node cell transmission model (CTM) is able to simulate arterial traffic with relative error flows on the order of those obtained in CTM freeway models. However, a CTM arterial model may require significantly more calibration parameters than a CTM freeway model (e.g., signal timing plans and turning ratios at all intersections) and, more important, the arterial NGSIM traffic data used in this study is seldom available in most arterial networks. Arterial traffic inhomogeneity and other exogenous effects, such as pedestrian crossing traffic and right-turn-on-red vehicle flow, make modeling accuracy more challenging. The model accuracy can be improved if such events are modeled in more detail. In this simulation study presented in [29, 30], demand and split ratios were updated at an interval of 10 seconds. Unfortunately, such data quality is seldom available in most arterial networks.

Development of the Vertical Cell Model (VCM)

[38] attempts to adapt the Cell Transmission Model (CTM) to make it work in the arterial network. While CTM is generally accepted as a standard representation of traffic flows on freeways with long links and uninterrupted flows, less is known about the accuracy of CTM or other macroscopic queueing models on urban road networks with short links and frequent flow blockages due to signal control. In fact, almost all existing validations of CTM focus on modeling freeways. In this work done on the Connected Corridors deployment site, we aimed to provide evidence toward selecting the appropriate queueing model dynamics for use in analysis and control of a large-scale network of signalized traffic intersections. We introduce a new vertical queueing dynamics called the Vertical Cell Model (VCM) that incorporates a representation of link transit time and finite queue capacity. The linear link model of VCM provides an attractive new alternative to CTM for practical network-wide estimation and control procedures. We then compared the link outflow and density outputs of both VCM and CTM to a set of

high fidelity ground-truth observations on a multi-intersection segment of an existing urban roadway. Ultimately we provided a validation of both CTM and VCM for use in arterial networks which have minimal observed over-saturation. The development and validation of VCM is a first step toward a new control-theoretic approach to the operations of signalized intersections in a large-scale network.

Arterial Point Queue (PQ) Model and the Max Pressure Controller

[31, 32] presents a groundbreaking approach to both modeling and control of arterial traffic networks.

A novel mesoscopic Point Queue (PQ) model is introduced, which described the evolution of arterial networks as controlled store-and-forward (SF) queuing networks. In this modeling paradigm, vehicles at the links independently make turns at intersections with fixed probabilities or turn ratios and leave the network upon reaching an exit link. There is a separate queue for each turn movement at each intersection. These are point queues with no limit on storage capacity. Arterial network demand is modeled by vehicles entering the network at a constant average rate with an arbitrary burst size and moving with pre-specified average turn ratios.

A new max-pressure approach for controlling the signalized intersections of an arterial network is also introduced in [31, 32]. The control formulation assumes that at the beginning of each cycle, a controller selects the duration of every stage at each intersection as a function of all queues in the network. The max-pressure differs from other network controllers analyzed in the literature in three respects. First, max-pressure requires only local information: the stage durations selected at any intersection depend only on queues adjacent to that intersection. Second, max-pressure is provably stable: it stabilizes a demand whenever there exists any stabilizing controller. Third, max-pressure requires no knowledge of the demand, although it needs turn ratios. The analysis presented in the paper provides guaranteed bounds on queue size, delay, and queue clearance times.

[33] studies the simulation and control of a network of signalized intersections using the ”point queue” (PQ) simulation model. Vehicles are assumed to arrive at entry links from outside the network in a continuous Poisson stream, independently make turns at intersections, and eventually leave from exit links. There is a separate queue at each intersection for each turn movement. The control at each intersection determines the amount of time that each queue is served within each cycle. A vehicle arriving at an intersection joins the appropriate queue, waits there until it is served (its ”green light” is operated), then travels over the downstream link and joins the next queue or leaves if it is an exit link. The performance of the control scheme that is modeled using the PQ simulator is measured in terms of the length of each queue, the queue waiting time, and the travel time from entry to exit. Two sets of control policies are modeled and compared via PQ simulations for a fairly complex arterial network near the I-15 freeway in San Diego, California. The first is “fixed time” (FT) control, which generates an open loop periodic sequence of green light operations. The second is the “max pressure” (MP) in which the turn movement that is operated is a function of the queue lengths adjacent to the intersection. The simulations confirm the theoretical property of MP, namely that it maximizes throughput, whereas FT does not. The simulation study provides more details concerning the queue length distribution and the behavior of MP as a function of how frequently it is invoked. These details are critical in evaluating the

practicality of MP. The study shows that the PQ simulator is a versatile tool in the design of signal control.

In [34] different modifications of the max-pressure controller are analyzed and compared under the same demand scenarios. The mesoscopic model used for the simulation experiments is an extended version of the point queue (PQ) model introduced in [31, 32]. The results obtained demonstrate the efficiency of max-pressure algorithms, which, under certain conditions, can stabilize all queues of the system. The PQ mesoscopic simulation model was validated using the same the NGSIM Lankershim Los Angeles data that was used to calibrate and validate the CTM model in [29, 30].

In [53] we calibrate the PointQ for data from a small portion of the Huntington-Colorado I-210 arterial network, and again show the superiority of MP over the existing fixed time controller.

Signalized Intersections

[35] simulates a network of signalized intersections as a queuing network, and intersections are assumed to be regulated by fixed time (FT) controls, all with the same cycle length or period. It is shown in this paper that the state of the network evolves according to a delay-differential equation and that there exists a unique periodic trajectory to which every state trajectory converges. Moreover, if vehicles do not follow loops, the convergence occurs in finite time. This unique periodic trajectory determines the performance of the entire network.

This insight is used in [54] to propose an algorithm for calculating the optimum offsets in an arbitrary network. The algorithm is illustrated for the 13-intersection Huntington-Colorado I-210 arterial network. The performance of the ”optimum” offsets is compared with the existing offsets and decreases peak and average queues by 27 percent and travel time by 9 percent. The optimum offsets are calculated in 0.37 seconds on a standard laptop.

Traffic Management

[55] is addressed to transportation economists. It argues, based on many years of work in the TOPL and Connected Corridors projects, that congestion is due as much to ineffective management as it is to excess demand. Economists generally ascribe all congestion to excess demand.

Origin-Destination Estimation

[36] presents an approach to estimate Origin-Destination (OD) flows and their path splits, based on link traffic counts in the network. The approach called Compressive Origin-Destination Estimation (CODE) is inspired by Compressive Sensing (CS) techniques. Even though the estimation problem is underdetermined, CODE recovers the unknown variables exactly when the number of alternative paths for each OD pair is small. Noiseless, noisy, and weighted versions of CODE are illustrated for synthetic networks, and with real data for a small region in East Providence. CODE’s versatility is suggested by its use to estimate the number of vehicles and the Vehicle-Miles Traveled (VMT) using link traffic counts.

Queue Estimation and Modeling

In [37] an algorithm was developed to estimate queue length based on loop detector data, using the Hamilton-Jacobi framework. However, this approach was found not to be practical given the noise level in the data. In [38] a discrete-time point queue (DTPQ) model was developed and compared to an arterial cell transmission. In addition, a common framework was developed to analyze both CTM and DTPQ models. In order to feed this model with the proper boundary conditions (i.e., split ratios at the intersections), an algorithm was developed to estimate split ratios in real time. This algorithm was tested and provides good results even with aggregate data [39].

Facilitating Implementation of Traffic Responsive Plan Selection Operations

Typical traffic controllers can be operated with plan selection based either on time of day (using time-of-day or TOD mode) or on observed conditions (using a traffic responsive plan selection or TRPS mode). TRPS mode will enable a signal controller to use immediate feedback from local volume and/or occupancy sensors to choose a timing plan optimized for current conditions from a pre-programmed set of existing plans. While most of the implementation-oriented research performed to date on TRPS has focused on either small networks of less than five intersections or on artificial (theoretical) networks, several studies have shown that operating in a TRPS mode often has large potential for achieving delay reductions in highly varying or abnormal traffic conditions.

[52] proposes a new method for rapidly configuring TRPS system parameters for global delay reduction using only the set of signal timing plans that is already encoded in network controllers. This methodology is model-independent and therefore easy to implement on any network given reasonable knowledge of sensor placements and critical intersections. The “constraint” of using only existing signal plans makes this method more immediately useful than previous proposals, as it skirts the need for long and costly re-timing processes—but can still incorporate new plans as they become available. We believe that this will make the methodology very attractive to municipalities hoping to improve the efficiency of their existing automated signal control procedures without the expense of re-timing procedures or the need to acquire new hardware.

The work built procedures that could be implemented to calibrate this mechanism, and provide a proof-of-concept demonstration of the procedure which improves the theoretical performance of a real signal in terms of a simple estimation of intersection delay. Even without any real effort to tune or “optimize” the tools implemented in the proposed calibration procedure, the resulting controller was shown to achieve a delay reduction that was very close to the optimal performance possible with the set of existing signal plans. Because the concept was designed to be applied on existing hardware using the set of signal plans already available, the algorithm is something that could be implemented practically immediately.

Additional Work

In addition to traffic flow management, part of the efforts devoted to the work have focused on estimation of traffic conditions on arterials, in particular using probe data. Topics covered include:

- Evaluation of variations of travel time in slow varying traffic conditions, based on LASSO algorithms. [40]

- Path inference filter, a new technique developed at Berkeley to integrate probe data into travel time estimation algorithms. This algorithm has been parallelized and implemented in the cloud using various computational platforms, in particular Spark. [41]
- Probabilistic formulation of queuing problems (i.e., understanding the expected lengths of queues rather than their instantaneous values). [42]
- Map attribute inference problems (learning the features of a map, such as stop signs, from probe data). [43]

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